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MOVEMENT OF AN AUTONOMOUS SYSTEM ALONG SPECIFIED WAYPOINTS WITH CONSIDERATION OF THE TERRAIN

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ABSTRACT

In urban environments with specified types of obstacles and a paved ground autonomous systems are already able to drive along specified waypoints and to fulfill tasks independent from a human operator. In open space with unpaved terrain, changing weather conditions and several changes of the illumination of the environment due to the movement of the sun, clouds etc. this task becomes quickly a challenging one which is not completely solved until now. Also the solution presented by us will not allow a successful movement on all kinds of terrain and in all weather conditions. But for some common weather conditions and a limited set of terrains the algorithms presented have a high chance in being successful to fulfill a waypoint navigation task.
We will present the idea behind the concept, discuss some of the underlying algorithms in comparison with possible alternatives and show selected simulation results gathered with these algorithms.
This includes the classification of the terrain into different types based on a fixed cell size and a specific A* derivate for the trajectory generation in real time that allows vehicle velocities up to 20 km/h.

***Index Terms*—** path planning, A*, waypoint following

1. INTRODUCTION

Unlike UAVs that have already reached the market and that are operating since some years in more and more countries this status is still a future scenario for UGVs. Some of the reasons are that in the air collision can only occur with other flying objects and, depending on the type of mission, with high mountains. As a consequence normally takeoff and landing are the most dangerous parts of such missions. For UGVs that are not leaving the ground the environment is the mayor problem, as this is permanently changing and often only small parts of the environment can be passed with an UGV. The result is that in controlled areas like container terminals with defined environmental settings automatic guided vehicles are already able to operate. The same applies to situations with warehouses or inside large factories. In all these cases a defined and controlled environment allows to use unmanned systems for everyday tasks, but when it comes to complex urban, suburban, or even unpaved areas the situation changes as analyzed in [4] where different reasons for failures of UGVs and additionally the capabilities of the algorithms are listed. In addition to the unclear legal situations regarding liabilities also the environment itself often is the reason why UGVs are unable to fulfill complex tasks outdoors without support by a human operator.
The effect is that this field is still a subject of various research projects from multi-national organizations like European Union or the European Defence Agency as well as in many countries of the world also national programs, including a high number of universities, research institutes and industrial partners are involved. Results from these researches regarding the control of UGVs in outdoor environments and the required underlying technologies can be found for example in [6], [3] and [5].
Apart from different types of leader-following tasks that have been handled for example in [8] and [1] the other major task with plenty of potential for possible applications is the capability to move along defined waypoints. This can be interesting for border patrolling tasks, farming tasks or delivery tasks. The idea is that a human operator sets some waypoints which can be located, depending on the mission, in several kilometers distance from each other. The UGV is then performing the desired mission along these waypoints. With an increasing distance between the waypoints and the complexity of the environment the required planning capabilities normally increase with the consequence that more sensors and a better understanding of the surrounding environment by the UGV is required. The alternative is to set waypoints closer to each other and to ensure that the paths between them are largely drivable. This requires more attention during mission planning by the human operator, but thereby the chance is much higher that the UGVs mission is able to be fulfilled with a selected set of existing algorithms. In such a mission a human operator would, for example, place waypoints

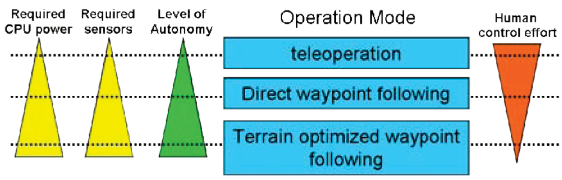

Fig. 1. Operation Modes for waypoint following

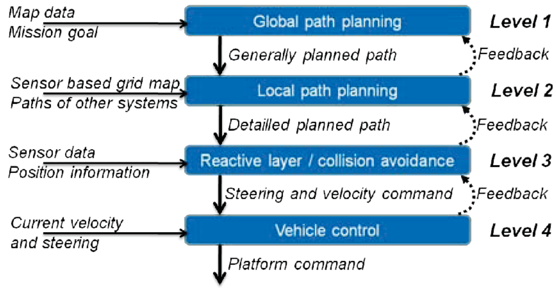

Fig. 2. Control loops that are integrated in the system

at each road crossing in order to define the streets to be used by the UGV. Moreover, positions where the street should be left would be defined by these waypoints.
The concept we want to present in this publication is a mixture of both. The human operator is free to define a mission. If the level of detail is too low, the robot will try on its own to reach the waypoints that are lying far from each other. As this can result in situations in which the UGV is unable to find a solution on its own a human supervisor is required who can react on alarms from the system. Possible ways of interaction are defining more detailed waypoints or selecting a teleoperation mode, as for example areas that are covered by water cannot be crossed automatically, because the system is unable to detect in advance how deep the water will be.
The general concept for the UGV control will be introduced in chapter 2 and then in chapter 3 an introduction is given regarding the possible definition of waypoints for our system. Then briefly the algorithms for global path planning, that are used in cases when a low resolution global map of the selected area is available in advance, are described in chapter 4. In chapter 5 the algorithm for the local planning is outlined. Finally some simulation results are shown in chapter 6 that are explaining the capabilities of this setting of algorithms and the general concept behind it.

2. ADAPTIVE ROBOT CONTROL

The concept of our interpretation of adaptive robot control is that the human operator can set a desired degree of autonomy for the UGV. The UGV is then trying to adhere to this whenever possible but changes it automatically whenever required. Furthermore, for each type of task the UGV has some different algorithms on board and can select automatically the one that is fitting best for the actual situation. This means that, for example, the UGV can have two self-localization algorithms that are running in parallel. One that requires GPS updates and one that has its focus on robustness in cases when GPS signals are not available. As a consequence the UGV is able to operate in situations with and without GPS signal simply by selecting the better performing algorithm. In a similar manner different path planners are available for mission planning and local planning based on the currently generated map delivered by sensor data interpretation. This concept allows being flexible in the sensor setting. The UGV platform has different small software services with single tasks which are parameterized using configuration files as input. It is also possible then to have different UGV platforms and different sensor types. By this, it is not required to decide a priori which algorithm will be the best and then to implement this one. In our approach there can be one algorithm for sandy surfaces, one for urban environments etc. and we do not need a perfect algorithm that is able to handle all these situations. This has the advantage that algorithms can be developed directly for single tasks without considering other situations. The disadvantage, however, is that the UGV has to select the best algorithm online and calculate more than one of them in parallel, which results in a higher CPU load.
Fig. 1 shows the different operation modes that the human operator can select as waypoint navigation modes with explanation regarding the required amount of CPU power consumption and number of sensors. Internally the UGV software additionally has a layer-based coordination concept that is shown in Fig. 2. Something similar to this has been developed and described already for UUVs in [5]. This concept is capable to use several developed software services also for other tasks like leader-following, wall-following or an automatic return-home mode.

3. POSSIBLE DEFINITIONS OF WAYPOINTS

Depending on the specific task and the training of the human operator it is required to have some adjustable parameters for each waypoint as follows:

- ⋆ accuracy of the waypoint in [m]
- ⋆ omittable yes/no
- ⋆ fixed sequence yes/no
- ⋆ fixed direction for passing [rad]
- ⋆ accuracy of the direction +/- [rad]

With these parameters is it possible to avoid that, due to suboptimal placing of waypoints, the UGV has to leave the street or that, in cases when a path to a waypoint is completely blocked, the mission is still able to

be completed by omitting the waypoint. In other cases it may be helpful if the UGV selects the best order for driving along the waypoints on its own. This is something that becomes interesting if only old maps of an area, that should be explored, are available or if the exploration of a region with many unknown obstacles is wanted. The reason in these cases is that the UGV is able to rearrange or to modify the order of the waypoints, depending on its current position, the detected obstacles, and the available surface information. The information regarding the direction is, according to our studies, only interesting in a few cases when an accurate movement is required, for example due to hidden detection markers in the ground of the passing of a laser beam that will start an automatic opening of a gate.
In addition to this waypoint information also forbidden zones (zones of exclusion) can be specified to ensure that the UGV is not entering restricted regions. The reverse may also be necessary, i.e., placing a forbidden zone around the area of operation to ensure that the UGV will not leave the defined area of operation due to obstacles or impassable terrain.

4. ALGORITHM USING GLOBAL VIEW

In most cases it is helpful if, before a mission starts, some information about the scenario is available, because based on this information a planned path from one waypoint to another can be calculated. This can help to avoid that the UGV drives into dead ends, or that it takes a far longer way than required to reach the waypoints, as on maps information about bridges, streets and rough terrain information is often available.
There are different planning algorithms available that are able to find an optimal path based on defined optimization criteria and the available information. Cases in which the information is available as digital map with vector data for the description methods like Mixed Integer Programming can deliver good results as explained in [7]. Alternative planning methods like Voronoi diagrams described in [5] can also be used. These methods are able to handle vectorized information using polygonal or ellipse models for the description of obstacles and can use vectorized sector description for the description and consideration of the terrain surface. In case of Mixed Integer Programming additionally a model for the non-holonomic constraints regarding the vehicle platform can be added to have a more or less realistic model of the steering capabilities of the UGV already during the planning phase. This is something that is not possible in several other optimization criteria like Voronio diagrams without large additional effort. In cases no digital map with vector data is available there are often only scanned maps or satellite pictures available. This information can only be used as information based on grid maps and as a consequence a different optimization algorithm is recommended as Mixed Integer Programming is delivering weak performance on grid-based maps. Algorithms like A* can fill this gap as they are directly working with discrete information and are able to handle obstacles and terrain information. With some extensions and modifications of the standard A* algorithm non-holonomic constraints of the UGV platform can be considered as described in [8].
In the simulation results presented later a grid-based map is used in combination with A*, because the use of the grid-based map has the advantage that the UGV is able to upgrade the grid map with its own gathered sensor information of the local surrounding. This is required as the local path planned could get trapped in a U-shaped type of obstacle or other difficult forms of obstacles. With the update capability of the global map the global planner is able to define a new path that avoids these obstacles and helps the local path planner not to get trapped again. In cases a global planner, that is using vectorized information, is used this is not easily possible, because a transformation of the information of the grid-based local map into vectorized information would be required.

5. ALGORITHMS USING LOCAL VIEW

For the local path planning based on the local map created from the sensor data of the UGV it is for our UGV important to have a fast algorithm that allows path planning with update rates faster than 10 Hz to ensure that the UGV is able to move continuously using the latest sensor information and to avoid collisions with moving obstacles. As described in the previous chapter we are using a grid-based map created from the sensor data. This map includes the gradient information and the terrain quality which is described by discrete values as shown in Tab. 1. To consider the non-holonomic constraints we are considering in the A* algorithm the direction from which a map cell is entered. We only allow that this cell is left in straight direction or at an angle that is less than the limiting angle that can be realized applying the maximum turning radius of the UGV. The details regarding the implemented algorithm can be found in [8] where the algorithm is used to fulfill a different task. Other methods like probabilistic roadmaps, Voronoi diagram, visibility graphs, or the potential field method have stronger limitations regarding the capability of the integration of the terrain types combined with gradient information of the terrain.
An interesting alternative to the use of the A* algorithm is the use of model predictive control. In this case the local path planning can be combined directly with the path following and can deliver directly the commands for the UGV platform. Such a method is described in [9] for UAVs without consideration of terrain types or gradient information. This method is currently not successfully completely realized based to our knowledge

Table 1. terrain quality classes

description	value
street - (center of the actual track)	10
street - (paved surface, tar)	20
pathway - (center of the actual track)	30
pathway - (grit, sand)	40
drivable 1 (flat terrain)	110
drivable 2	120
drivable 3	130
drivable 4	140
drivable 5	150
drivable 6	160
drivable 7	170
drivable 8	180
drivable 9	190
drivable 10 (tall grass, mud)	200
impassable (trees, bushes, rocks)	250
unknown	255

Fig. 3. Screenshot of the simulated environment

for this task, as the required setting containing the integration of terrain type information and gradient information results in an optimization task that is consuming more CPU power than that what is available based on our implementation concept. The result would be that updates couldn't be generated with a rate higher than 10Hz.

6. SIMULATION RESULTS

Tests with UGVs realized in hardware have the disadvantage that the environment is continuously changing and that the repeatability is, as a consequence of this, limited. This makes tests with different parameter settings difficult and therefore usually no absolute reference to identify small position errors is available, if the UGV itself is using already a self-localization with DGPS. As a consequence the results of the algorithms presented here and the concept for the waypoint following are taken from simulations. To give rough information about the level of detail that is available in our simulation a screenshot out of it is shown in Fig. 3.

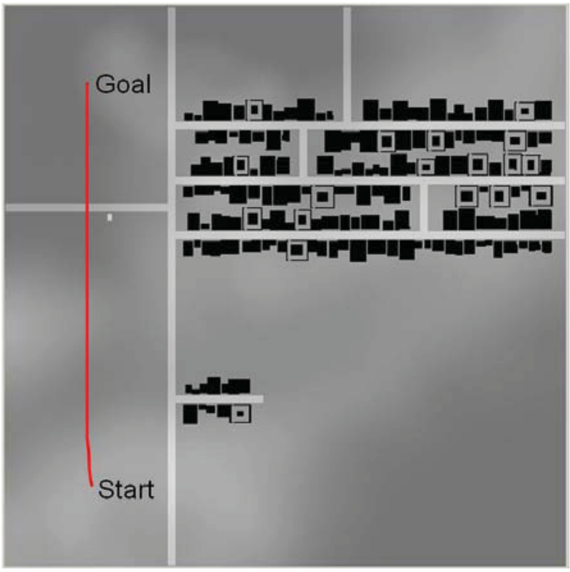

Fig. 4. Global planning only based on nonholonomic constraints using A*

In a first test the capabilities of the global path planner have been analyzed. Therefore a path between two waypoints had to be calculated twice i.e. once without the consideration of the type of terrain and gradient information and once with the complete consideration of the type of terrain and gradient. As shown in Fig. 4 and Fig. 5 the resulting planned paths are differing clearly. They have been visualized here on a mixed map that is combining height information and obstacles as well as streets. In case the information about the gradient and the terrain type is used the street is favored and, as a consequence, the path length is longer, but due to the weighting parameters in the A* optimization criteria the cost of this path is lower than the costs if the straight line from Fig. 4 would have been driven. Also more complicated tasks could be handled in the same manner, but then the explanation of all influencing effects becomes rather complicated and sometimes is not directly understandable in all cases without deeper investigations of the criteria and the algorithm implementation together with the exact values of the gradient and terrain-type maps.

In the second test the local path planner is tested based on local maps that have been created using information from a simulated 3D laser like the Velodyne HDL 64E. As shown in Fig. 6 the local path planner is able to handle the disturbed maps and to plan a path from the position $[900, 900]^T$ to the position $[900, 1050]^T$. The path in the figures is extended into the unknown blue area simply to show in which direction the next waypoint is placed. Outside the known area the path

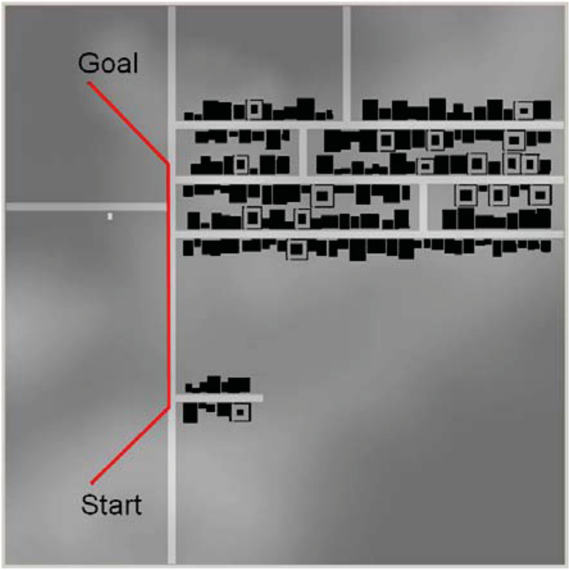

Fig. 5. Additional consideration of terrain type and gradient information for the global path planning

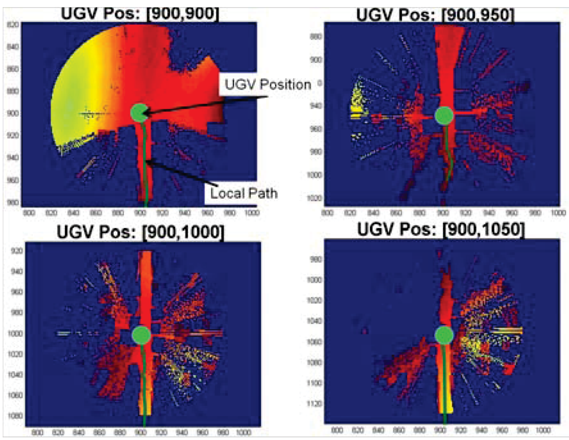

Fig. 6. Local path planning using maps created based on laser scanner information

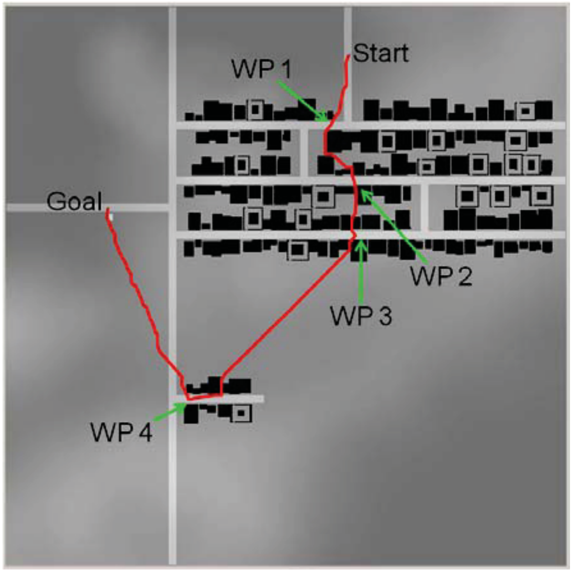

Fig. 7. Test run with combined global and local path planner without initial knowledge of the map

is simply realized as a straight line. In cases the map is not fully explored up to the maximum distance the planned path is ending inside the local map as shown in Fig. 6 for the case $[900, 950]^T$. In this case the UGV is still moving into a possible dead end as the information available is too limited at that time for the UGV to decide if a possibility to continue will become available in that direction or not. In such cases the UGV is always optimistic and exploring the area before deciding to continue to try to reach the next waypoint by moving into another direction first.

In the last test shown in Fig. 7 no initial map is given to the UGV but both the global and the local planners are running. This is necessary to ensure that the UGV cannot get trapped in an area with a high number of obstacles that cannot be solved based on the information available from the local map. As no information is available before the mission has started the UGV is leaving the street at label (1) due to the fact that it is at that time not clear whether the street will guide the robot to the next waypoint. Later the UGV is often not using the streets and is driving cross country, because based on the parameter setting the robot is able to pass this outdoor terrain and due to the missing global map at the beginning the UGV does not have enough information about the streets. The reason is that in our current setting no prediction of the continuation of a detected road is performed and, as a consequence, the unknown terrain has the same value in each cell of the grid map.

7. CONCLUSION AND OUTLOOK

It has been shown that the concept for waypoint-following is working in simulation and that it will allow an UGV to fulfill tasks defined by a human operator in most cases autonomously without any request of support by the human operator. As the local map information might in some situations be more disturbed than in the simulation that has been used for the development and test of the algorithms there might still be situations when the human operator is required to take control. This may be necessary in situations like puddles filled with water or mud as in such cases the UGV is unable to determine the depth, and if no path around can be found the operator will receive the task to move the robot over the puddle or to stop or to abort the mission if no passage can be found. In the near future we will perform experiments with one of our test UGVs to also prove the algorithms in reality under different weather conditions.

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